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TEMPORAL FREQUENCY OF RADIO EMISSIONS FOR THE APRIL 25, 1984 FLARE

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ABSTRACT

The National Geophysical Data Center archives data of the solar-terrestrial environment. The USAF Radio Solar Telescope Network (RSTN) data allow performance of time series analyses to determine temporal oscillations as low as three seconds. For our study, we selected the X13/3B flare which erupted in region 4474 (S12E43) on 24-25 April 1984. The soft X-rays, 1-8 A, remained above X-levels for 50 minutes and the radio emissions measured at Learmonth Solar Observatory reached a maximum of 3.15×10^5 SFUs at 410 MHz at 0000 UT. A power spectral analysis of the fixed frequency RSTN data from Learmonth shows possible quasi-periodic fluctuations in the range two to ten seconds. Repetition rates or quasi-periodicities, in the case of the power spectral analysis, generally showed the same trends as the average solar radio flux at 245 and 8800 MHz. The quasi-periodicities at 1415 MHz showed no such trends.

1. Introduction

Solar radio emissions in the microwave range have been monitored for many years, but only within the last 20 years have investigators realized the rapid fluctuations superimposed on these bursts were not "noise" or interference. Since then, several physical mechanisms have been proposed to explain these rapid fluctuations. They may be caused by a modulation of the source radiation by waves or oscillating magnetic fields, or by quasi-periodic accelerations of electrons or successive occurrences of elementary bursts either in a single or several source regions (Zodi et al. 1984). The last two proposed explanations will be resolved with improved spatial resolution of the recording instruments. The first explanation involves several mechanisms of solar physics which may be distinguished by their fundamental periods as they give clues to the scale of the emitting source.

Zodi et al. (1984) separated these quasi-periodic pulsations into categories. The first, and most common, class occurs in chains of a few pulses (not more than a few tens of pulses) separated by nearly constant time intervals such as the burst analyzed by Parks and Winckler (1969). A second class consists of long-lasting uniform oscillations which persist throughout the event, such as the 28 March 1976 burst examined by Kaufmann et al. (1977). The third class consists of the extremely fast (tens of milliseconds) structures superimposed on mm-microwave bursts, with repetition rates (quasi-periodicity) that are directly proportional to the average flux level (Zodi et al. 1984).

These quasi-periodic fluctuations have been detected over a broad range of periodicities. Kaufmann et al. (1984) detected some of the finest structure yet with a periodicity at 30-60 ms and a "slow" structure at 1 s, whereas, Cribbens and Matthews (1969) reported a periodicity of 385 $\pm$15 s. Quasi-periodic fluctuations in the range 2-10 s have been reported by many authors (Janssens et al. 1973; Kaufmann et al. 1972; Cliver et al. 1976; Gaizauskas and Tapping, 1980; Urpo et al. 1981; Kaufmann et al. 1977; and Zodi et al. 1984).

This RSTN data set was chosen for several reasons. Although the RSTN is of fairly low resolution, 1 s, compared to Itapetinga recordings, it has provided a nearly continuous, 24-hour record of solar radio emissions since 1981. Also, the RSTN data is readily available from the NGDC in Boulder, Colorado, USA. Additionally, most studies of quasi-periodic bursts have used microwave bursts with peak fluxes on the order of hundreds of SFUs (1 SFU = 10^{-22} watts/m^2/sec) or less and durations of minutes; whereas, the burst presented here had a peak flux on the order of a few hundred thousand SFUs at 245, 410 and 610 MHz and a duration of hours. This burst also had very distinct impulsive and gradual phases. The length of the burst gives a sufficiently large number of data points to analyze for "true" periodicities in considerable detail using power spectral analysis techniques at various stages of the burst. Finally, although the data is not of sufficient resolution for "quasi-quantization" studies, the temporal resolution is sufficient for studies of "elementary" bursts with durations of 5-20 s (Sturrock et al. 1984) and "quasi-periodicity" in the range of seconds to hours.

2. Equipment

The RSTN network monitors the Sun with an analog sweep frequency recorder and at eight discrete frequencies, i.e., 245, 410, 610, 1415, 2695, 4995, 8800 and 15400 MHz. It consists of three observatories: Sagamore Hill, Massachusetts (actually a prototype RSTN site); Palehua, Hawaii; and Learmonth, Australia. Except for a "window" over Europe, these sites provide nearly 24-hour coverage of solar radio emissions. The RSTN discrete frequency radio telescopes monitor the power output of the solar disk and not just for a specific region. The system consists of an automatic tracking antenna system, a radiometer, an automated "event" detection system and an analog recording system. The radiometers employed in the RSTN system are Dicke radiometers and are designed to automatically compensate for rapid gain changes within the equipment. The Dicke operates at a 500 Hz rate and is located between the antenna signal and the matched load, a 50 ohm precision noise source. The RSTN system uses shielded coaxial cable for frequencies below 8800 MHz and precision wave guides for 8800 and 15400 MHz to transfer the energy from the feed to the receiver system. The 30 MHz intermediate frequency (IF) section within each receiver limits the signals to an approximate 8 MHz bandwidth.

The lower frequencies (245-1415 MHz) have double IF amplifiers to provide approximately 55 dB gain for the medium and low gain channels and 99 dB gain for the very high and high gain channels. The output from the 30 MHz IF amplifier is detected and filtered to extract the audio modulation introduced by the action of the RF switch by the lock-in amplifier. Details are listed by frequency in Table 1 (Air Weather Service Pamphlet 105-61).

Table 1
A summary of technical data for the discrete frequency radiometers and their associated antennas.

Frequency (MHz)	HPBW (deg)	Antenna Diameter (m)	Effective Bandwidth (MHz)	Efficiency (%)	Maximum Flux (SFUs)
15400	1.49	0.9144	14	45	50,000
8800	.976	2.4384	14	22	50,000
4995	1.72	2.4384	14	31.5	50,000
2695	3.187	2.4384	7	45	50,000
1415	6.115	2.4384	7	50	100,000
610	4.068	8.5344	2	50	500,000
410	6.0	8.5344	2	53.2	500,000
245	10.09	8.5344	2	55	500,000

3. Data and Data Reduction

Although we had data for all eight frequencies from about 30 minutes before the event to four hours after the burst maximum, we selected only three of the frequencies (245, 1415 and 8800 MHz) and limited our analysis interval to no more than 15 minutes (900 points). We also limited the analysis to four intervals: the preburst or interval A, the impulsive rise or interval B, the post-maximum or interval C, and the gradual or interval D. Figure 1 shows the general trends of the entire burst for the three frequenies produced from 20-second averaged data from 2330 UT on 24 April to 0400 UT on 25 April. The analysis intervals are 15 minutes each except for interval B where the duration depends on the implusive rise to maximum time.

Data quality should be good. The relative values used are reportedly accurate to within 1 SFU (Near 1985). As mentioned in the previous section, the equipment automatically attempts to remove system noise. In addition,

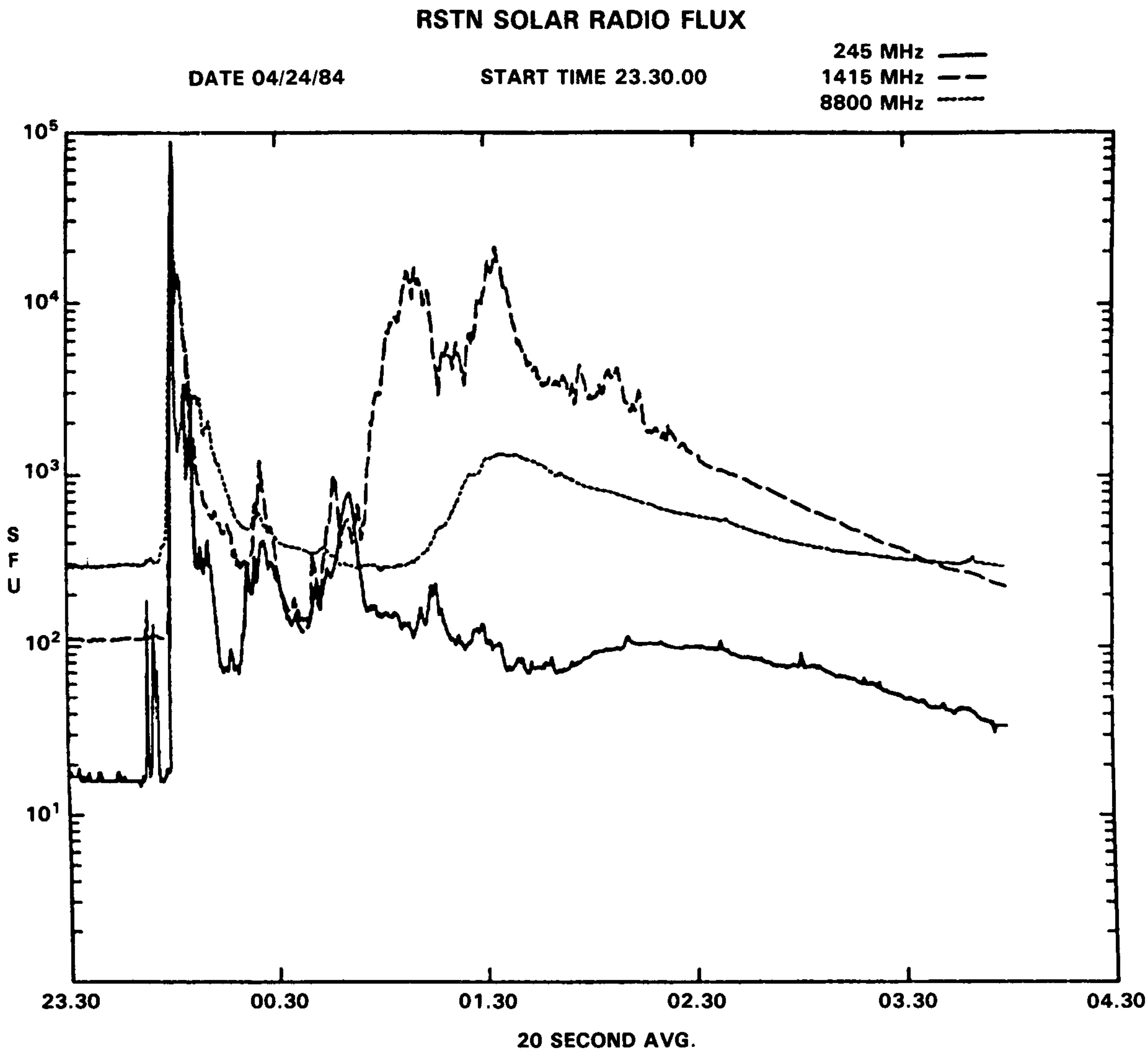

Figure 1. Plots of the 24-25 April 1984 radio burst using 20-second averages at 245, 1415 and 8800 MHz. Data from Learmonth, Australia.

since Learmonth is remotely located in northwest Australia (Exmouth), local interference should be minimal. Finally, since the RSTN system measures the flux of the whole disk, pulsations due to the antenna beam oscillating across a fixed source, as region 4474, are not a factor. Unfortunately, this also introduces uncertainty as to the source of the pulsations. However, except for the preflare interval (A), the average flux is on the order of a few thousand SFUs and any emission from nonflaring regions should be negligible. Higher-time resolution plots of intervals A-D are shown in Figures 2-5.

The data were filtered to remove all periodicites greater than 10 s. This was done for two reasons. The first, and most obvious, reason is that we were only looking for periods on the order of two (the Nyquist frequency) to ten seconds. The second reason involves the desire to know whether the peak is at or below the 95% confidence level, which is shown on the normalized Fourier power plot. Unfortunately, once a peak drives the trace above the 95% confidence level, the confidence level of subsequent peaks is uncertain. Therefore, we wanted the first peak to exceed the 95% confidence level to have a periodicity of 10 seconds or less. In an attempt to resolve peaks of less than five seconds when there was a significant peak between 5 and 10 s, we also filtered out all periodicities greater than 5 s for intervals C and D.

4. Data Analysis

The Fourier power spectrum, the normalized Fourier power spectrum, and the maximum entropy spectrum analysis (MESA) were estimated for each frequency for each interval using the filtered data. The Fourier power spectrum and normalized power spectrum are used to determine, statistically, whether a given peak is significantly above background noise. The maximum entropy is an attempt to measure the degree to which the randomness of the data has been lost or gained by using power spectral analysis. Nine hundred points (15 minutes) were used as input to the filter routine. However, since the filter reduces the number of points, only 850 points were input into the power spectral analysis program, except for interval B. As part of the power spectral program, the significance was estimated both by the Fisher statistic and the 95% confidence interval in the normalized Fourier power plot.

To check for any dominant preflare periodicities due to system, environmental, or local sources, interval A was included as one of the power spectral analysis intervals.

Following the Fourier analysis, we went back into the data plots to locate the "quasi-periodicities" found in Tables 2-3. This was done by measuring the peak to peak temporal spacing. We then marked those peaks which closely ($\pm$ .5 s) agreed with the Fourier "quasi-periodicities".

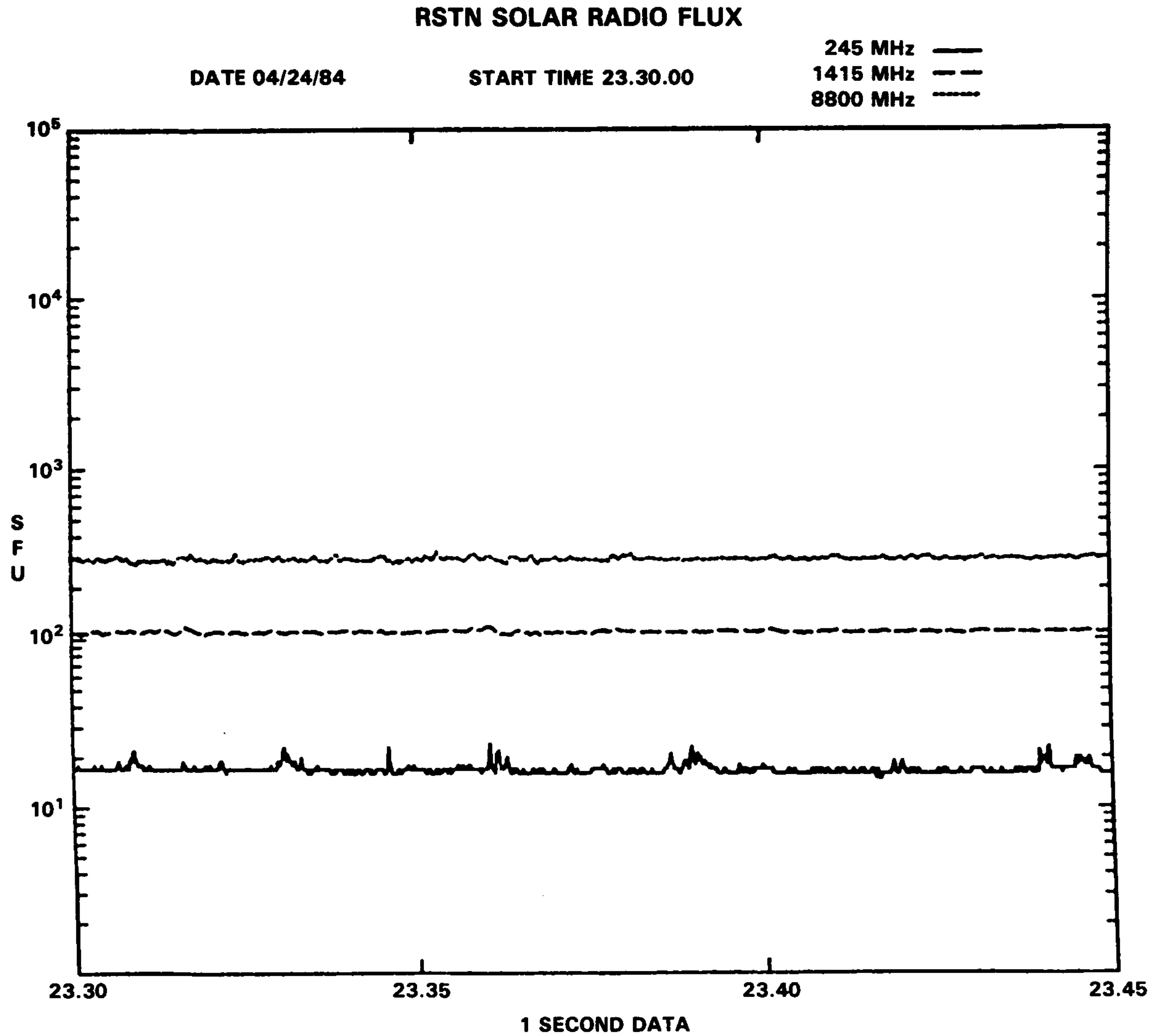

Figure 2. Preflare interval (interval A) for 245, 1415 and 8800 MHz. Data are at 1-second resolution from 2330 UT to 2345 UT on 24 April.

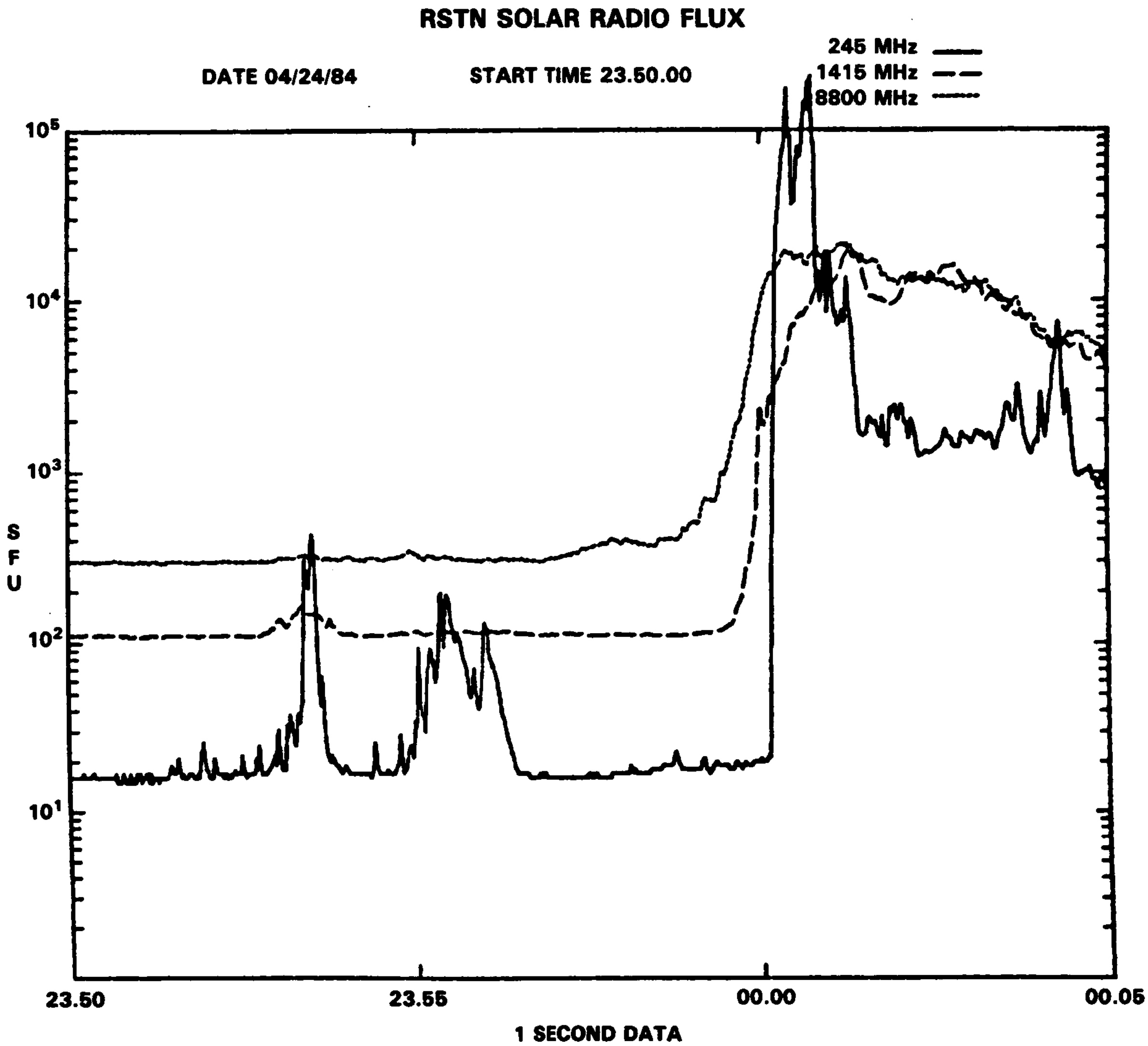

Figure 3. Impulsive Rise (interval B) for 245, 1415 and 8800 MHz. Data are at 1-second resolution from 2350 UT on 24 April to 0005 UT on 25 April.

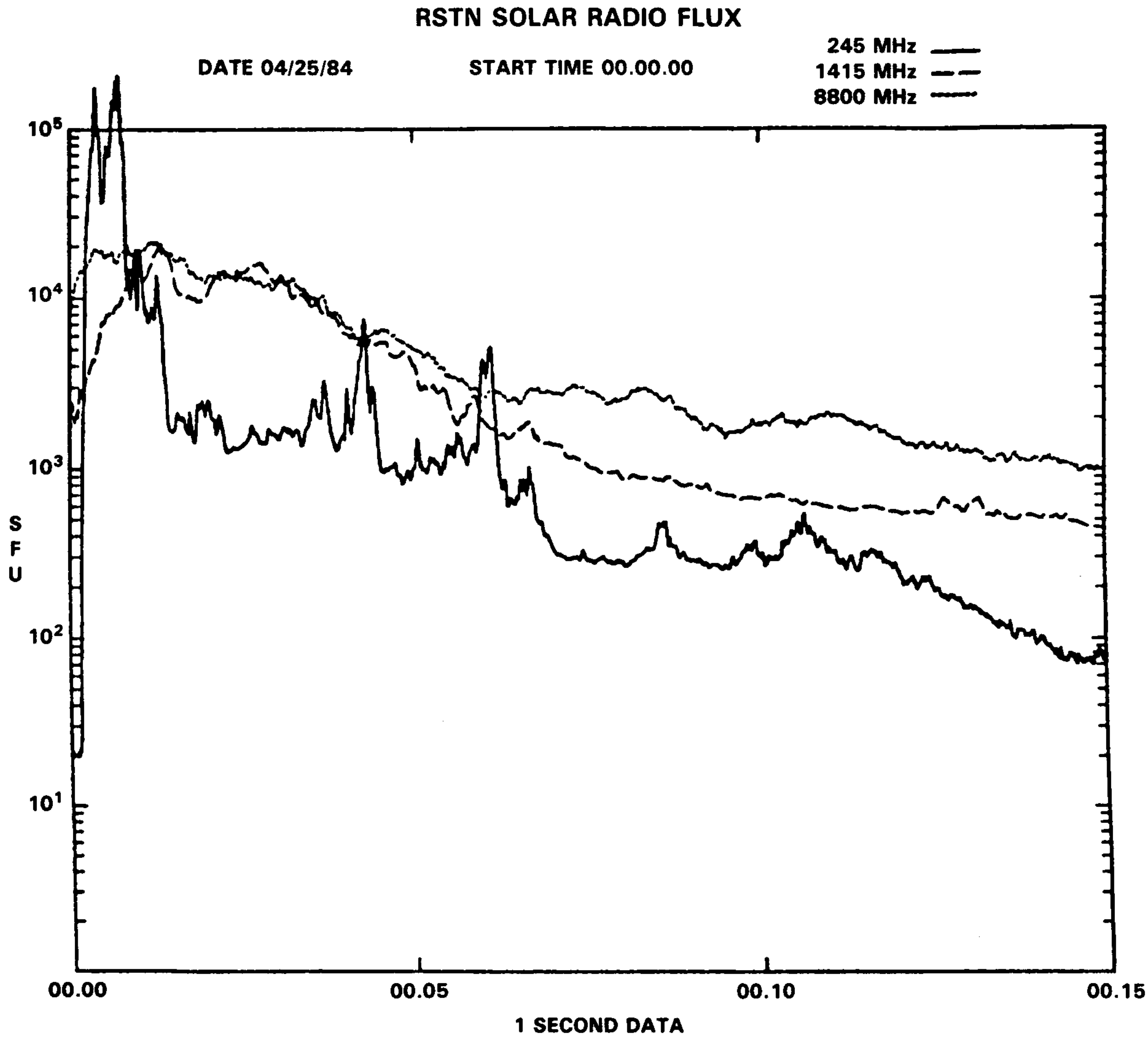

Figure 4. Post-maximum (interval C) for 245, 1415 and 8800 MHz. Data are at 1-second resolution from 0000 UT to 0015 UT on 25 April.

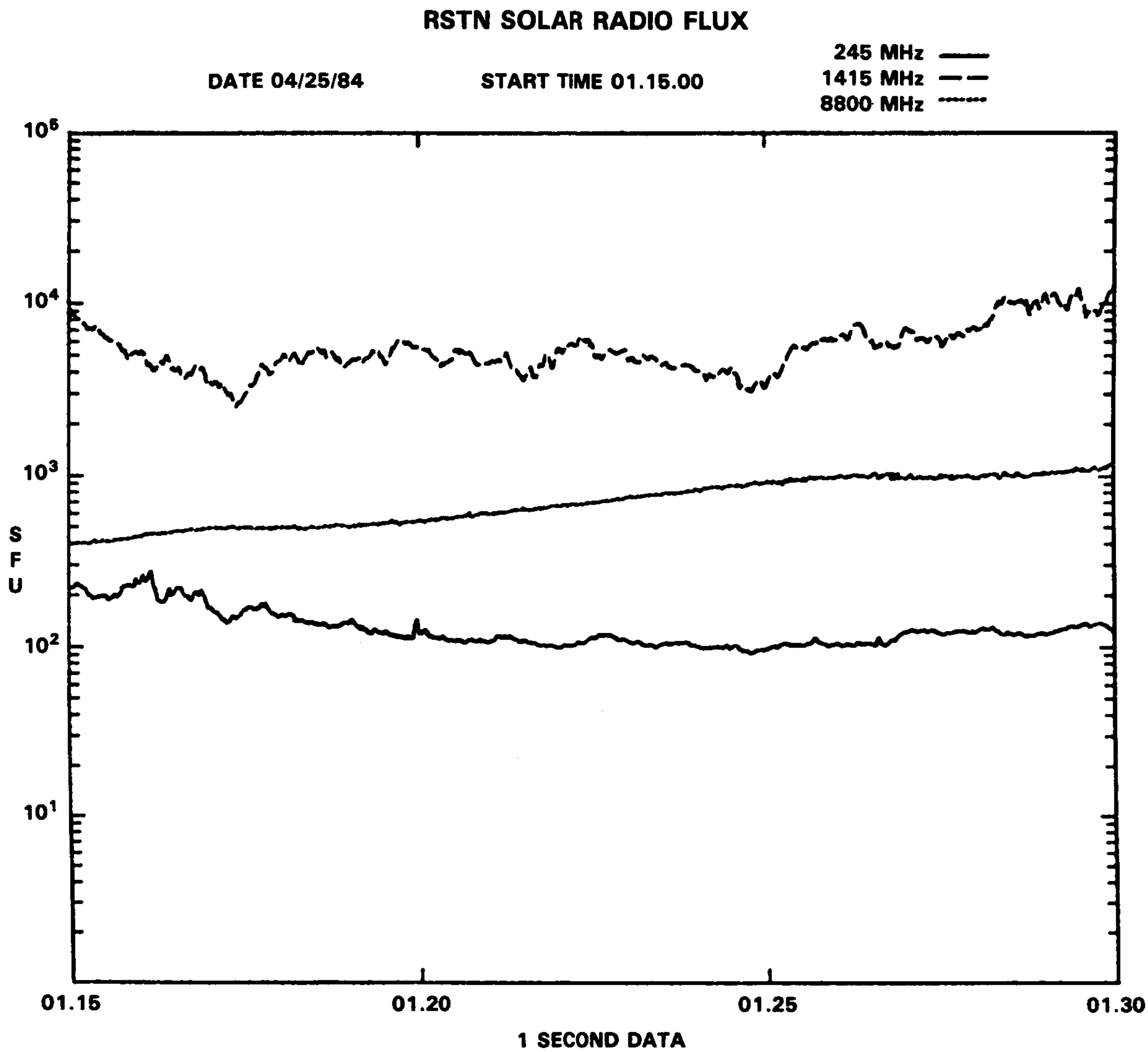

Figure 5. Gradual phase (interval D) for 245, 1415 and 8800 MHz. Data are at 1-second resolution from 0115 UT to 0130 UT on 25 April.

5. Results

For interval A, no periods with a 95% or greater confidence level, hereafter referred to as significant, occurred at 410 or 610 MHz. The maximum peak at 1415 MHz did not prove significant, but a secondary peak at 3.7 s did prove significant. Maximum, significant periodicities ranged from 3.7 to 8.2 s. A summary of the preflare interval (interval A) is found in Table 2.

Table 2
Summary of significant periods for interval A and whether they are significant based on the Fisher statistic and normalized power spectrum.

Frequency	Interval	Quasi-Period (sec)	Fisher	Normalized
245	2330-2345	7.02	Yes	Yes
410	2330-2345	None		
610	2330-2345	None		
1415	2330-2345	3.7	Unk	Yes
2696	2330-2345	8.17	Yes	Yes
4995	2330-2345	4.78	Yes	Yes
8800	2330-2345	8.02	Yes	Yes
15400	2330-2345	6.2	Yes	Yes

For the impulsive phase (interval B), we did not have a sufficient number of data points at 245 (30 points) and 1415 MHz (100 points) to give significant results. Therefore, the results at these two frequencies will not be presented. We did have a sufficiently large number of points at 8800 MHz (220 points) and found a double peak in the Fourier power curve around 6.8 s, which did prove significant (Figure 6). Interval B results are summarized in Table 3.

The post-maximum interval (interval C) was analyzed in two runs. In the first run, the data was filtered to remove periodicities greater than 10 s; in the second, periods greater than 5 s were filtered out. In the first run, significant peaks occurred at 8.4 s and 9.8 s for 1415 and 8800 MHz, respectively. The peak at 5.03 s was not significant using the Fisher statistic, but did prove significant using the normalized Fourier power plot (Figure 7) and the maximum entropy plot. In the second run, significant peaks occurred at 2.1 s, 4.4 s, and 3.3 s at 245, 1415, and 8800 MHz, respectively. See Table 3.

Interval D was analyzed using the same techniques as interval C. For the first run significant peaks occurred at 7.7 and 8.1 s for 245 and 1415 MHz, respectively. The significant peaks during the second run were 3.9 s based on the Fisher statistic, Fourier power spectrum, and the maximum

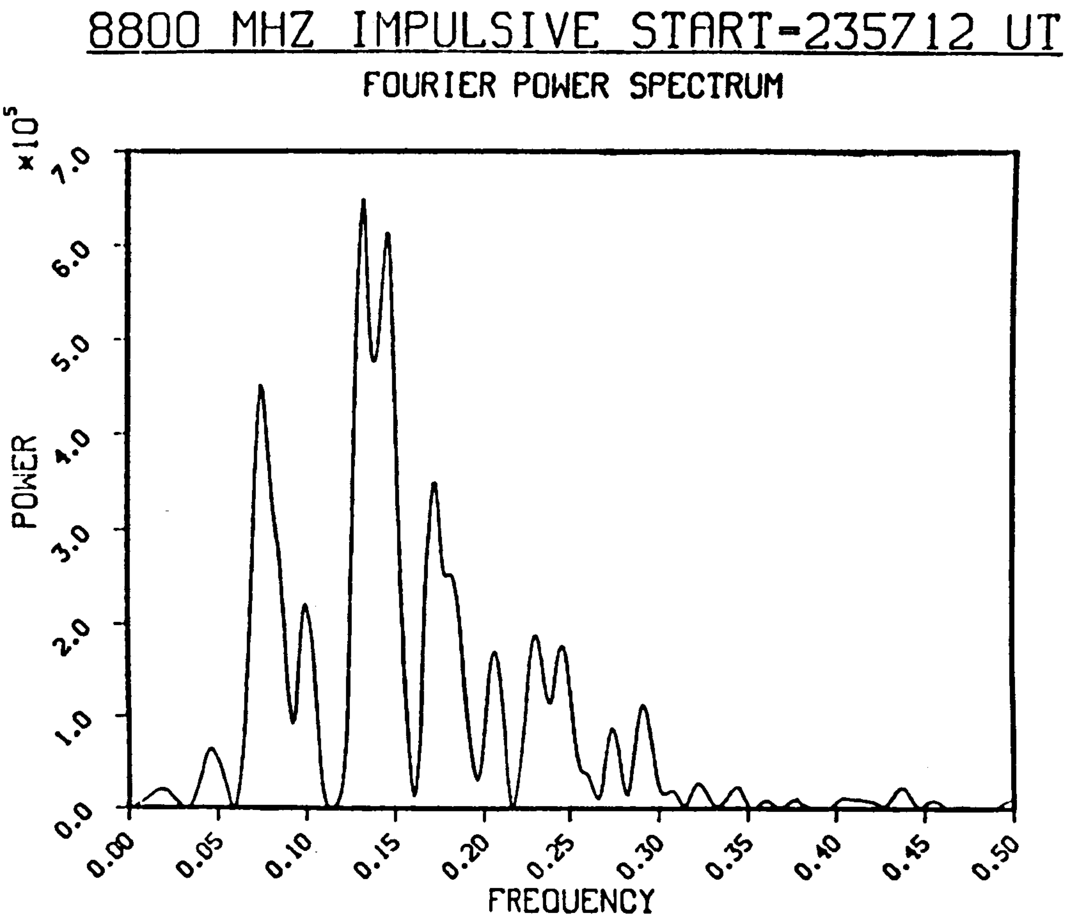

Figure 6. Fourier power spectral plot for 8800 MHZ during the Impulsive phase or interval B. Data have been filtered to remove periodicities greater than 10 s. Data are at 1-second resolution from 2357.2 UT on 24 April to 0000.87 UT on 25 April.

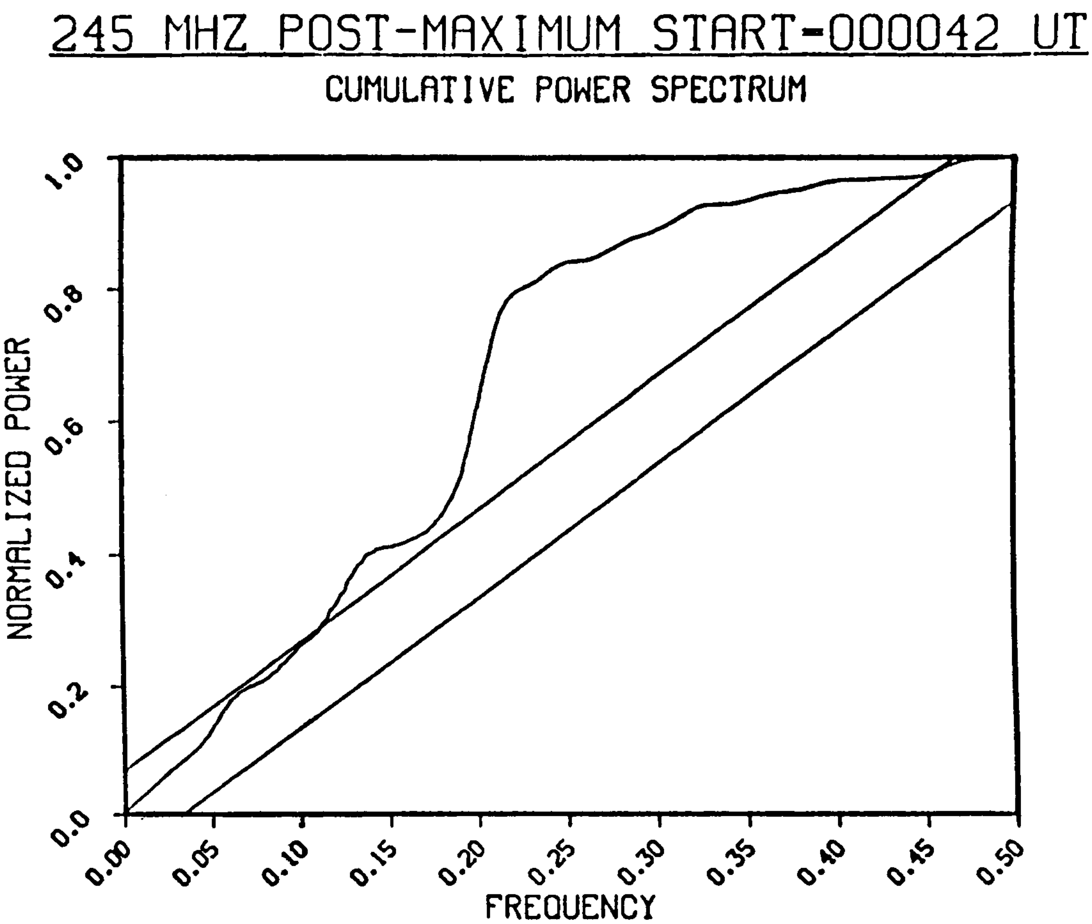

Figure 7. Cumulative Fourier power spectrum plot for 245 MHz during the Post-maximum or interval C. Data has been filtered to remove periodicities greater than 10 s. Data are at 1-second resolution from 0000.7 UT to 0014.87 UT on 25 April. The portion of the curve above the upper diagonal line is significant at the 95% confidence level.

entropy plots (Figure 8); but it was 3.1 s based on the normalized Fourier power plot. The peak at 1415 MHz occurred at 4.0 s. No significant peaks were noted at 8800 MHz.

Table 3
Summary of significant periodicities for intervals B, C and D and whether they are significant based on the Fisher statistic and the normalized power spectrum.

Frequency	Interval	Time (hhmmss)	Quasi-Period (sec)	Fisher	Normalized
8800	B	235712-000111	6.8	No	Yes
245	C10	000042-001541	5.03	No	Yes
245	C5	000042-001541	2.1	Unk	Yes
1415	C10	000216-001715	8.42	Yes	Yes
1415	C5	000216-001715	4.45	Unk	Yes
8800	C10	000111-001610	9.77	Yes	Yes
8800	C5	000111-001610	3.32	Yes	Yes
245	D10	011500-013000	7.66	Yes	Yes
245	D5	011500-013000	3.95	Yes	Yes
1415	D10	011500-013000	8.09	Yes	Yes
1415	D5	011500-013000	4.67	No	Yes
8800	D10	011500-013000	None		
8800	D5	011500-013000	None		

Although crude and not nearly as complete as the Fourier analysis, the peak to peak measurements did yield some interesting results. First of all, those peaks exhibiting the "quasi-periodic" oscillations indicated by the Fourier analysis generally occurred in pairs, and were very rarely organized into groups of more than three successive pulses. Notable exceptions to this generalization occurred at 1415 MHz beginning at 0013.36 UT (Figure 9), and at 8800 MHz beginning at about 0012 UT (Figure 10) on 25 April 1984. In the first case (1415 MHz), there were five peaks spaced at approximately 8.4 s intervals, and in the second case (8800 MHz) there were four peaks spaced at approximately 9.8 s intervals. Secondly, the longest "quasi-periodic" episode lasted on the order of one minute, which was considerably shorter than our 15 minute analysis intervals. Finally, we noted intervals where two "quasi-periodic" episodes were occurring simultaneously though out of phase with respect to each other (Figure 11).

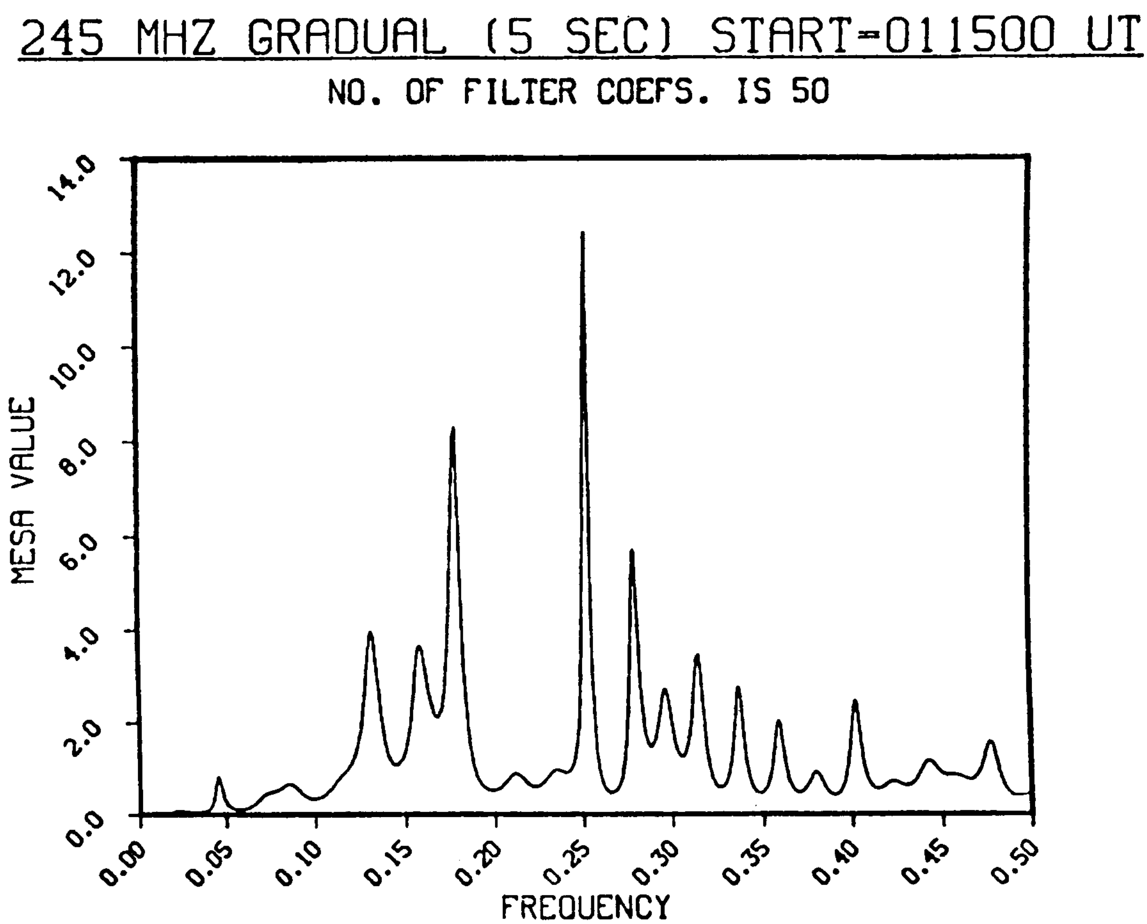

Figure 8 . Maximum entropy plot for 245 MHz during the Gradual phase or interval D. Data has been filtered to remove periodicities greater than 5 s. Data at 1-second resolution from 0115 UT to 0129.17 UT on 25 April.

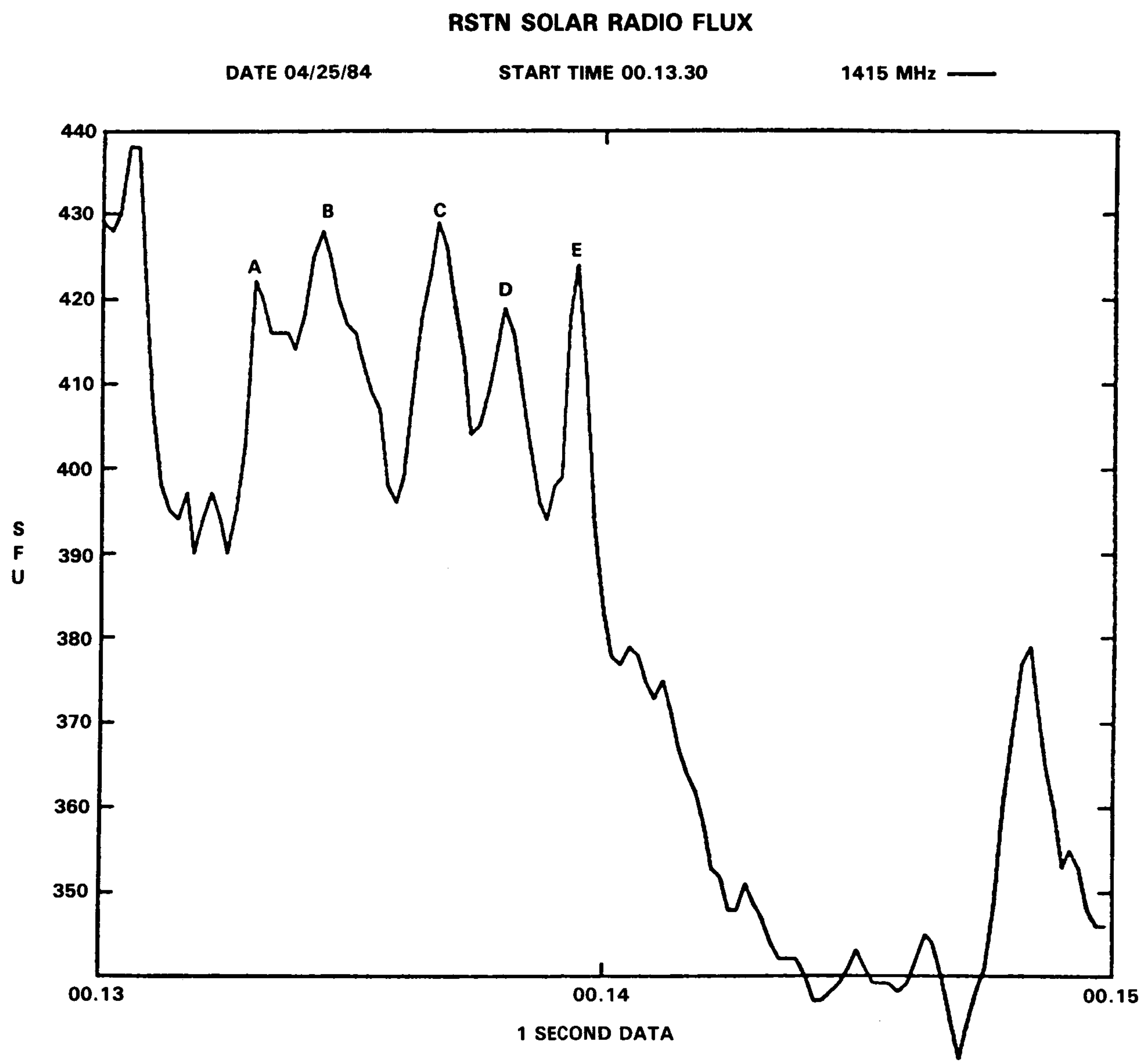

Figure 9. Quasi-periodic pulses at 1415 MHz. Data are at 1 s resolution from 0013.5 to 0015.5 UT on 25 April 1984.

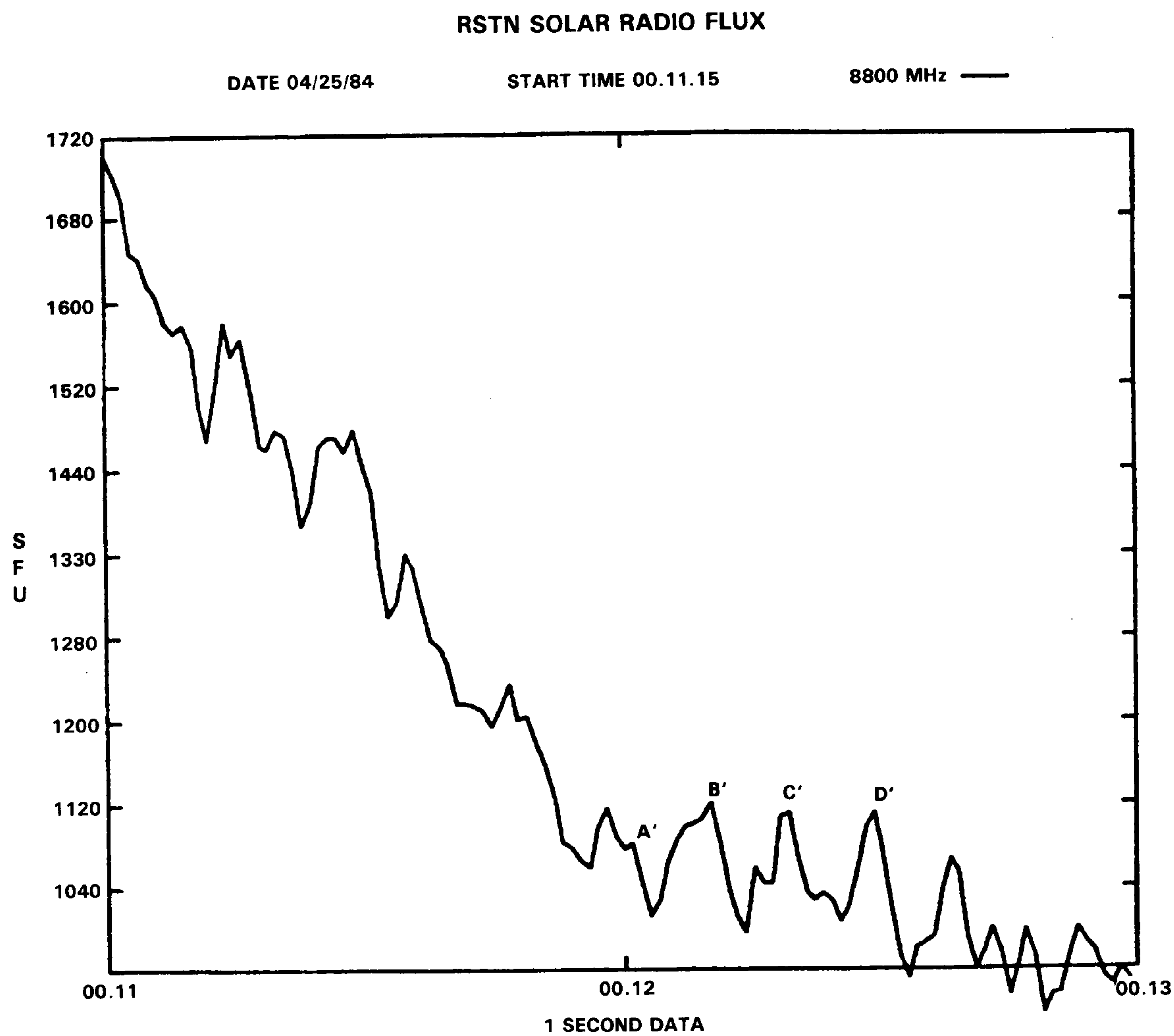

Figure 10. Quasi-periodic pulses at 8800MHz. Data are at 1 s resolution from 0011.25 to 0013.25 UT on 25 April 1984.

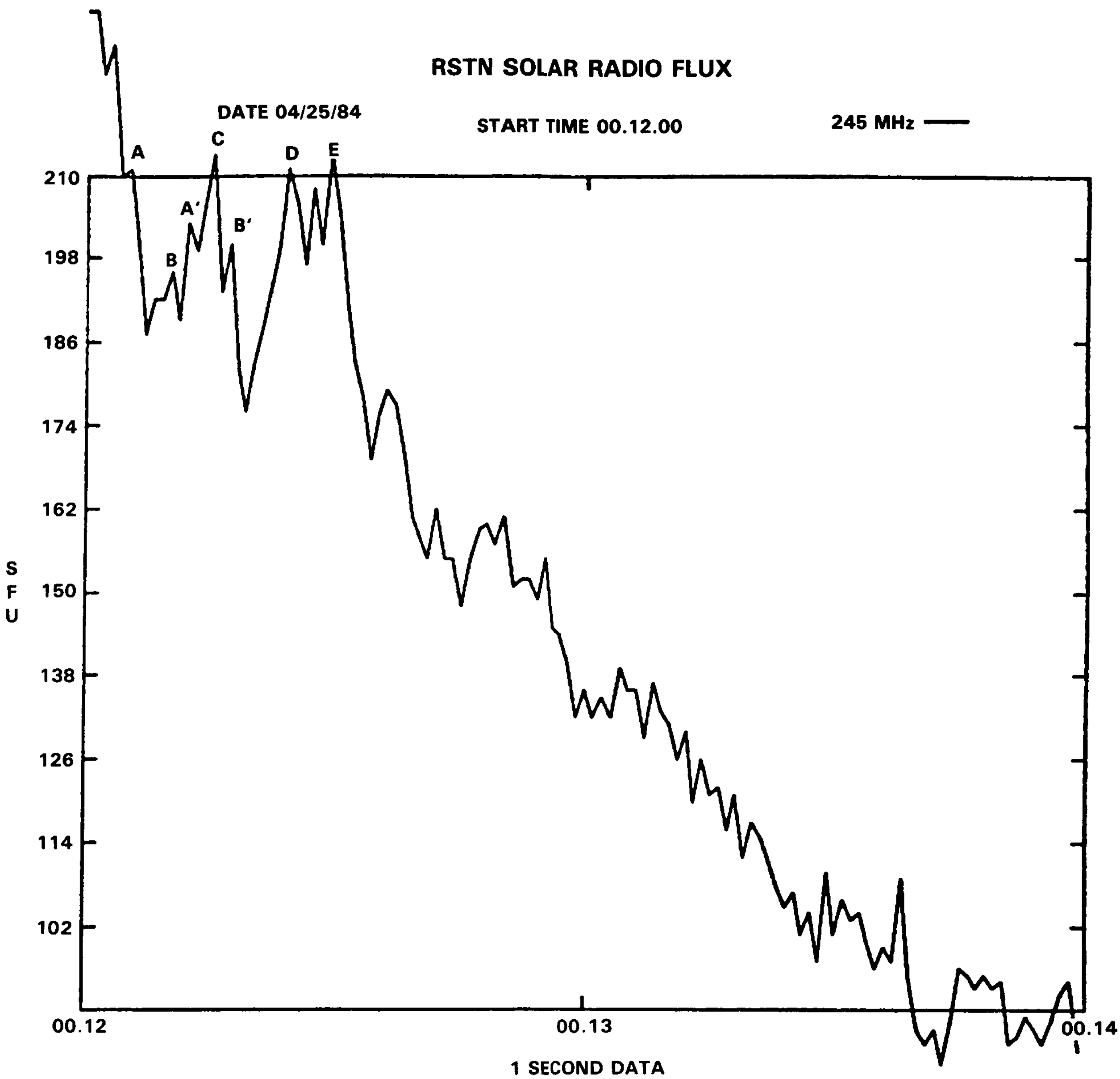

Figure 11. Overlapping (out-of-phase) quasi-periodic pulsations at 245 MHz. Data are at 1 s resolution from 0012 to 0014 UT on 25 April 1984.

6. Discussion

In this study, we sought to define the dominant periodicities in the range two to ten seconds in each of three radio frequencies monitored by the RSTN telescopes during each phase of the flare. The observed "quasi-periodicities" seem real since observed trends in periodicity at 245 MHz and 8800 MHz fit well with what would be expected based on Kaufmann et al.'s (1980) findings concerning the relationship between changing repetition rates and changing radio flux. For instance, Figures 2, 4 and 5 show an increase in repetition rates for the post-maximum phase and then a decrease by the gradual phase. These observations are consistent with the results of the power spectral analysis which show the same trend. Also, the apparent loss of significant periodicity at 8800 MHz by the gradual phase supports our premise that the periodicities during the preflare interval at this frequency were caused by the "background" solar emission. The absence of any significant periodicity during interval D is probably due to the relative insignificance of the "background" emission when compared to the average flux of 600 SFUs, which is well above quiet sun values. Indeed, the power spectral analysis at 8800 MHz shows the largest frequency during the impulsive phase, a smaller frequency during the post-maximum phase and the disappearance of any significant frequencies by the gradual phase. Figure 5 confirms this decrease in repetition rate by the gradual phase at 8800 MHz.

For interval A, the spread in periodicities and the absence of a dominant periodicity throughout all eight frequencies suggest that the data is free from strong periodicities in the range two to ten seconds attributable to broadband system noise or local interference. However, the Fourier power spectrum plot for 610 MHz (Figure 12) clearly shows the data is "noisy". A possible source for some of this "noise" could be rounding of values, especially at lower frequencies where the variance is of the same order as the data accuracy. For example, the periodicity at 245 MHz during interval A appears questionable. It is uncertain whether the observed periodicity results from rounding of values due to the very small amplitudes of the the fluctuations, 1 to 5 SFUs, or from the cumulative effect of many, very short-lived bursts with peak fluxes around 10 SFUs (evident in Figure 2). Another explanation could be the changing or unstable periodicities noted when we searched the plots for the Fourier "quasi-periodicities". In this case, there might be significant periodicities, but these periodicities would not remain constant throughout the analysis interval (Rust 1985). At higher frequencies (greater than 2695 MHz), the observed periodicities seem to result from a "background noise" from the Sun, but they may also be due to a succession of small, impulsive bursts or some atmospheric phenomena. However, the possibility that they may be due solely to some random process cannot be eliminated.

Based on the appearance of our Fourier power analysis plots, it becomes evident that there are no "true" periodicities; but we did find evidence of "quasi-periodicities". We use the term "quasi-periodic" because the observed periodicities tend to occur over a range of values evidenced by double or even multiple peak maximum, the peaks were not necessarily of equal amplitudes, and their temporal spacing could only be determined to

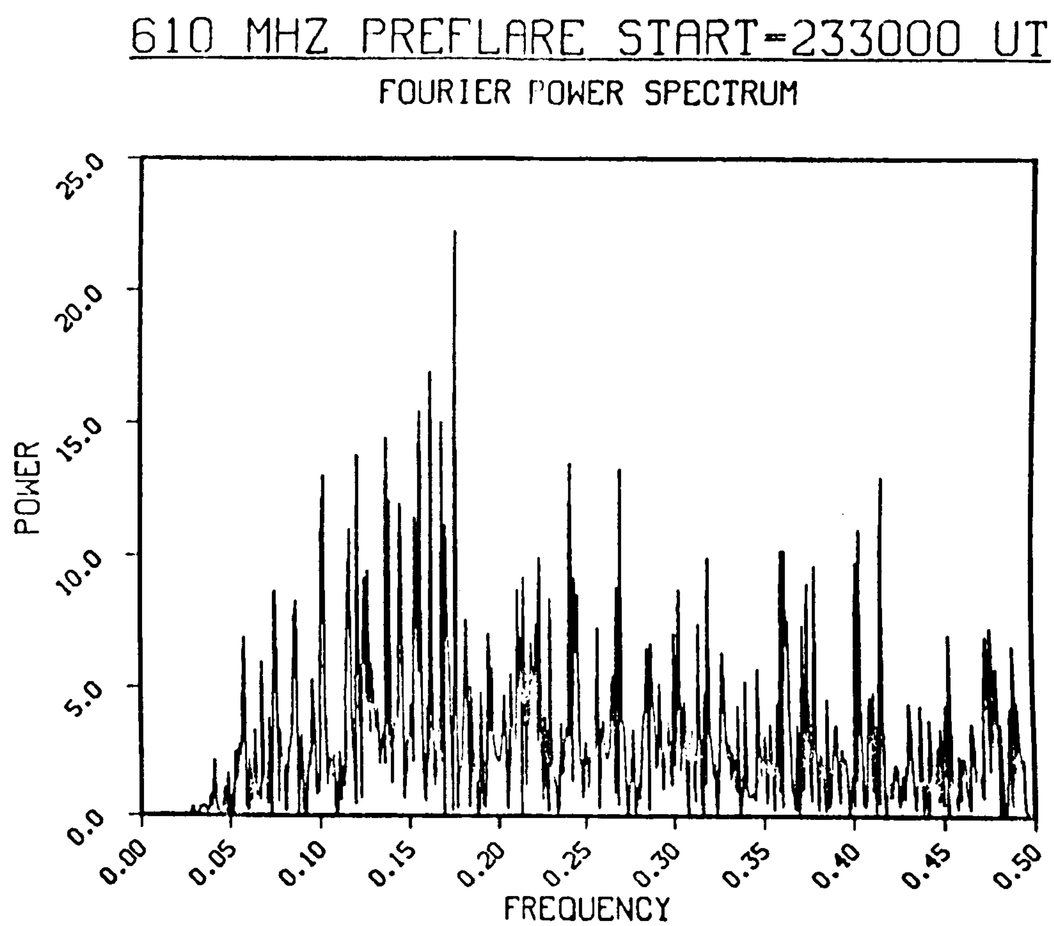

Figure 12 · Fourier power spectrum plot for 610 MHz during the Preflare interval or interval D. Data has been filtered to remove periodicities greater than 10 s. Data are at 1-second resolution from 2330 UT to 2344.17 UT on 24 April.

closely fit the Fourier values since the analysis program does not identify those peaks contributing to the "quasi-periodicity". The "quasi-periodic" episodes shown in Figures 9 and 10 (interval C) seem to closely fit the "quasi-periodic" events of the Parks and Winckler (1969) type. However, the vast majority of the peaks fitting the Fourier results occurred only in pairs indicating a random process rather than some physical mechanism. We, therefore, felt that the Fourier analysis techniques did not show conclusively that "quasi-periodicity" was present in all intervals in which they showed peaks in the power spectrum curves at the 95% confidence level. Based on the results of our subsequent searches for "quasi-periodicities", we felt Fourier analysis techniques do not adequately analyze for the presence of periodicities.

The suggested presence of two, out-of-phase, "quasi-periodic" events occurring simultaneously as shown in Figure 11 may indicate two emission sources. Indeed, observations from Tokyo Astronomical Observatory, Japan, did show two flaring areas within the region after 0100 UT (they were not observing before this time) (Kai, 1985). The presence of two emission sources would certainly contribute to making any results ambiguous. Additionally, the peaks analyzed were composed of an overlapping fine structure poorly resolvable using 1 s data (Kaufmann, 1985).

Our results may have been more conclusive had we analyzed more events, or if we had had some correlative data. As it turned out, Palehua Solar Observatory observed the event manually but was unable to record the radio data due to electrical power problems. This eliminated our hopes for simultaneous observations from two observatories using the same equipment and monitoring the same frequencies. These simultaneous observations are particularly critical for microwave frequencies below 10 GHz since radio emissions in this range do not correlate well with hard x-ray emissions.

Finally, our observations of quasi-periodicities of 4, 6, 9 and 10 seconds agree fairly well with quasi-periodicities reported by Cliver et al. (1976) using 2.8 GHz and with Kaufmann et al. (1977), who used 7 GHz data. Our use of a highpass filter is similar to work done by Urpo et al. (1981).

7. Conclusions

From our analysis, we conclude the following: (1) The RSTN data does contain a significant amount of "noise" which should be filtered out if one is interested in the very fine structure in the data. (2) The "noisiness" of the Fourier plots is partially due to shifting periodicities (Rust 1985). (3) Periodicities in the range two to ten seconds should be resolvable from the RSTN data, but higher resolution data would have been more desirable since the longest interval of "quasi-periodicity" noted was on the order of one minute. (4) These "quasi-periodicities" are similar to those reported by others at other microwave frequencies. (5) Simultaneous observations are critical for studies in this range of frequencies because Fourier techniques do not appear to adequately rule out periodicities due to random processes. (6) Analysis intervals should be on the order of one to two minutes for periodicities in the range two to ten seconds.

8. Acknowledgments

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